

EFFECTS OF STEP SIZE AND BREAK-POINT CRITERION ON KEYPECKING
BY PIGEONS ON PROGRESSIVE-RATIO SCHEDULES OF FOOD DELIVERY

By

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Keypecking by pigeons was maintained by progressive-ratio schedules of food delivery, in which the number of pecks required for food presentation increased arithmetically from one ratio to the next. In Part 1 (seven subjects), each session continued until five min passed in which no keypecks were recorded, and in Part 2 (five subjects), each session continued until 15 min passed in which no keypecks occurred (this period of time is termed the break-point criterion). Data collected in each session included the last completed ratio (i.e., the break point), the total number of ratios completed, the total number of pecks, and the length of each pre-ratio pause. Successive conditions arranged different step sizes, and each condition remained in effect for at least 25 sessions and until behavior appeared stable. Data taken from the last 10 sessions of each condition indicated that, in general, average break points were relatively unaffected by step-size magnitude, whereas the average number of ratios completed and the average total number of responses per session declined across increasing step sizes. For every subject, pre-ratio-pauses were relatively short and

fairly constant in duration across a number of ratios in the progression, after which pause durations increased rapidly. Larger step sizes resulted in this rapid increase of pause durations occurring after fewer ratio completions. The relation between the average number of completed ratios and step size observed in this experiment (and in a reanalysis of data taken from previous reports) was described well by a power function ($y = b * x^a$, in which y refers to the average number of completed ratios, x refers to the step size, and a and b are fitted parameters determining the slope and vertical displacement, respectively, of the function). Increasing the break-point criterion from five to 15 min resulted in increased values of b , whereas parameter a was relatively unaffected. The present results relate to current research in basic behavior analysis, behavioral pharmacology, and behavioral economics.

INTRODUCTION

Schedules of reinforcement are among the most powerful and widely used tools in experimental psychology. As Zeiler (1984) and others (e.g., Kelleher & Morse, 1968; Sidman, 1960) have noted, schedules both establish and maintain lawful patterns of behavior and may also determine to a large extent how other variables will influence behavior. Psychologists have made liberal use of the latter function, employing schedules in numerous settings to study a tremendous variety of behavioral patterns across a wide range of species. This practice resembles the lay culture's aphorism, "when you have a hammer, everything begins to look like a nail." It appears, perhaps unfortunately, that while many psychologists have been busy hammering away at the world's nails, the tool itself may have received less attention than it deserves.

A good example of an often used but hardly examined tool is the progressive-ratio (PR) schedule of reinforcement. In the original description of PR schedules (Findley, 1958), a number of responses was required for a reinforcer presentation, and that number increased from one reinforcer delivery to the next. A parameter termed the "step size" determined how rapidly the ratio requirements increased. For example, a step size of 100 (i.e., PR 100) would deliver the initial reinforcer after 100 responses, the second after 200 responses, and so on (this is an example of an arithmetic progression; a geometric progression would increase the ratio requirements by a fixed proportion, rather than a fixed amount). The defining features of this schedule, then, were that (a) a number of responses (i.e., the "ratio") was required for reinforcer delivery and (b) this number increased across ratios. Subsequent experimenters added

other features to the schedule that have become relatively commonplace, and these will be discussed in more detail below.

Although PR schedules made their first appearance almost 40 years ago, and their popularity among researchers has grown phenomenally (especially in the past fifteen to twenty years), very few experiments designed to describe the effects of manipulating fundamental schedule variables (e.g., step size) have been published. This dissertation reports the results of an attempt to investigate these issues. In the following sections, outlines of the burgeoning set of research programs employing PR schedules will be sketched, beginning with a description of the initial experimental questions the schedule was designed to help answer. Two following sections then summarize the many experimental topics in which PR schedule performance maintained by (a) food delivery and (b) drug infusions has been treated as a behavioral baseline (and the procedural innovations associated with this practice). A final section will outline the specific rationale and design of the present experiment in more detail.

History and General Characteristics of PR Performance

Findley (1958) was the first to employ PR schedules. He did so in a series of experiments investigating keypecking by pigeons in a situation in which subjects chose between two options (i.e., concurrent schedules). His procedure was designed to specify the conditions under which pigeons would "switch" from one schedule to another, and so the switching response was made explicit and could be counted. More specifically, in some conditions pecking one key produced access to food according to one of two PR 100 schedules (both options were correlated with distinctive stimuli), and pecking another key (switching key) shifted control from one schedule to the other. In addition to changing which schedule of reinforcement was in effect, switching-key responses also reset to its lowest value the response requirements in the PR schedule not currently available. Pigeons' keypecking became relatively efficient in these

conditions; in most cases, only one ratio in the currently available PR was completed, after which a switching response occurred, one ratio was completed in the other PR, and the pattern was repeated. Additional phases showed that (a) if more responses were required on the switching key to change the schedule in effect, subjects would sometimes persist beyond a single ratio in a PR, (b) if switching in one direction (i.e., from the schedule correlated with a red keylight to the schedule correlated with a green keylight) was made more difficult, relative to switching in the opposite direction (i.e., from green to red), subjects were more likely to complete more than one ratio in the schedule that was more difficult to exit, and (c) if one schedule's step size was smaller than another's, pigeons completed more ratios and spent more time in the small-step-size option.

Cumulative records of keypecking in these experiments appeared very similar to those produced by subjects responding on fixed-ratio (FR) schedules of food delivery (e.g., Ferster & Skinner, 1957). That is, a short period of time in which no keypecks occurred was abruptly followed by a period in which response rate was relatively rapid and unchanging -- until the ratio was completed and a reinforcer was delivered. This pattern of responding has since been observed by a number of investigators across a number of procedural innovations (e.g., Baron, Mikorski, & Schlund, 1992; Hodos & Kalman, 1963; Thomas, 1974).

Hodos (1961) introduced a variant of Findley's procedure that treated the PR schedule as a technique that could measure "reward strength." In his procedure, PR schedules were studied in isolation (i.e., not as one component in a concurrent schedule), and a session continued until a period of time (15 min) passed in which the subject (a rat) failed to make the designated response (a lever press). The last ratio completed by the subject before the session ended was termed the "breaking point," and the period of time without a response required to terminate a session was called the

"break-point criterion." Hodos argued that this general procedure could measure reward strength (or, in other terms, reinforcer efficacy), in that better rewards ought to lead to higher breaking points. And in this experiment, as expected, rats' breaking points increased as a function of concentration of sweetened condensed milk. This line of reasoning, that performance on PR schedules can be treated as an index of reinforcer efficacy, has stimulated a tremendous amount of research, portions of which will be discussed further below.

In a similar vein, others have used performance on PR schedules as an index of motivation. For example, Gilbert (1967) found that day-to-day changes in rats' body weights were highly correlated with day-to-day changes in breaking points. Since manipulating body weight may be construed as a motivational operation, and PR schedule performance appears to be quite sensitive to changes in body weight, some investigators have used the schedule to assess motivation across different subjects' body weights (e.g., Lawrence & Illius, 1989), between species (e.g., Eastman, 1971), between sexes (e.g., van Hest, van Haaren, & van de Poll, 1988), between strains of rats (e.g., Brito, 1985), and in depressed humans (e.g., Hughes, Pleasants, & Pickens, 1985).

Food-Maintained PR Responding as a Baseline

Performance on PR schedules of food delivery has been utilized by many investigators as a baseline behavioral phenomenon. That is, once responding has been established on a PR schedule of food delivery, other variables are applied and their effects are assessed on PR performance. These other variables have included reinforcer magnitude or volume (e.g., Baron et al., 1992; Cheeta, Brooks, & Willner, 1995; Hodos, 1961; Hodos & Kalman, 1963; Skjoldager, Pierre, & Mittleman, 1993), magnitude or general form of the PR increment (e.g., Hodos & Kalman, 1963; Uzunoz, 1979), acute and/or chronic drug administration (e.g., Buffalo, Gillam, Allen, & Paule,

1993; Cheeta et al., 1995; Dantzer, 1976; Ferguson & Paule, 1993; Jones, LeSage, Sundby, & Poling, 1995; Macenski, Schaal, Cleary, & Thompson, 1994; Merigan & McIntire, 1976; Paule et al., 1992; Thomas, 1976; Thompson, 1972a, 1972b), manipulation of air pressure and air content (e.g., Thomas, 1974, 1976), lesions of specific areas in the brain (e.g., Roberts, Loh, Baker, & Vickers, 1994; Stewart & Blampied, 1975), pre-session feeding, extinction, and alterations in response effort (e.g., Ferguson & Paule, 1995; Skjoldager et al., 1993), reinforcement-schedule history (e.g., Cohen, Pederson, Kinney, & Myers, 1994; Tatham & Wanchisen, 1994), and the presence of alternative-response options (e.g., Dardano, 1968, 1973, 1974; Dardano & Sauerbrunn, 1964; Hodos & Trumble, 1967; Mazur & Vaughan, 1987; Wanchisen, Tatham, & Hineline, 1988). Many of these studies have focused exclusive attention on alterations in breaking point as evidence of a variable's effect, but some have included data describing the manner in which other aspects of PR performance (e.g., the total number of responses emitted, total number of reinforcers earned, pre-ratio pausing, etc.) are concomitantly altered.

Comparing the effects of any two variables within or across the categories outlined herein on PR performance must be qualified by acknowledging substantial procedural differences across laboratories. Potentially significant factors, such as step size, break-point criterion, and reinforcer type have varied widely across studies. For example, some investigators use the conventional "time without a response" break-point criterion, but the duration of this period has varied from three (e.g., Dantzer, 1976) to 15 min (e.g., Merigan & McIntire, 1976). Others have employed a break-point criterion that specifies a temporal limit for completing each ratio, and the duration of this period has ranged from eight (e.g., Macenski et al., 1994) to 60 minutes (e.g., Thompson, 1972a). Some procedures set a time limit on overall session duration; several reports from the same laboratory (e.g., Buffalo et al., 1993; Ferguson & Paule,

1993; Paule et al., 1992) have embedded PR schedules in a multiple-schedule (cf. Ferster & Skinner, 1957) context, and PR components were limited to 10 min.

The nature of the ratio progression has also varied across studies using food as the reinforcer. Most have arranged arithmetic ratio progressions, with step sizes ranging from one (e.g., Dantzer, 1976) to 100 (e.g., Findley, 1958), but some have used geometric PRs (e.g., Johnson, Tribblehorn, & Collier, 1993; Stewart & Blampied, 1975; Stewart, Blampied, & Hughes, 1974; Uzunoz, 1979), and others have used more complicated algorithms to generate a progression of ratios (e.g., Roberts et al., 1994). In sum, one should use caution when attempting to compare the effects of different variables on PR performance, since major procedural differences across reports are the rule, rather than the exception.

Reinforcer Magnitude

Progressive-ratio performance, like most behavior controlled by schedules of food delivery, can be altered by changing characteristics of the food used as a reinforcer. Two early studies in Hodos' laboratory (1961; Hodos & Kalman, 1963) found that breaking points were an increasing function of both the concentration and the volume of sweetened condensed milk. This relation has since been replicated and extended in studies altering reinforcement magnitude by varying the number of sucrose pellets (e.g., Cheeta et al., 1995; Skjoldager et al., 1993). Baron et al. (1992) showed that pre-ratio pausing by rats pressing a lever on a PR schedule of milk delivery increased in an orderly, but nonlinear, fashion across the ratio progression: pauses were relatively short in duration across a number of ratios, after which pauses abruptly increased in length. In addition, they found that greater concentrations of milk both (a) prolonged the period in which short pauses were observed and (b) maintained greater breaking points.

Size or Nature of the PR Increment

Although the size or nature (i.e., arithmetic, geometric, etc.) of the step size appears to be a potentially significant determinant of PR performance, surprisingly little research has examined this issue in detail. Hodos and Kalman (1963) reported that as step size increased (range: two to 40), so did breaking points of rats for which pressing a lever was maintained by liquid reinforcers; they also demonstrated that food deprivation resulted in upward shifts of this function. Their conclusions, however, were based upon only six sessions of exposure to each step size, which is significantly less experience than most investigators report as necessary to establish stable patterns of responding on many schedules of reinforcement (e.g., Baum, 1993; Cumming & Schoenfeld, 1960), and no conditions were directly replicated. Uzunoz (1979) found that step size in a geometrically increasing progression (range: 1.10 to 1.12) had no systematic effect on breaking points when presses by rats on one of two levers produced food (i.e., only one lever was "active," but no distinctive stimuli were associated with which one it was); during conditions in which only one lever was available, however, breaking points generally increased with step sizes (range: 1.05 to 1.09) on a schedule with geometrically increasing ratio requirements.

Acute and/or Chronic Drug Exposure

Summarizing across a number of studies (although the procedural caveats noted above are especially relevant here), acute administration of chlordiazepoxide, phenobarbital, *d*-amphetamine, scopolamine, diazepam, and cocaine has been observed to produce elevated breaking points at some dose (usually a relatively small to intermediate-sized dose), whereas acute administration of carbon monoxide, methyl nitrate, caffeine, pentobarbital, methadone, buprenorphine, and raclopride has resulted in either decreases or no effect on breaking points. Unfortunately, in several of these reports, only one dose was tested; dose-effect assessments would be invaluable in

drawing any conclusions about the effects of a given drug on PR performance. Significantly less research has been directed at assessing effects of chronic drug exposure on food-maintained PR performance. Repeated exposure to marijuana had no effect on the breaking points of rhesus monkeys whose lever presses were maintained by food (Paule et al., 1992), whereas repeated exposure to methadone and buprenorphine in rats resulted in the development of partial tolerance to drug-induced break-point reductions (Macenski et al., 1994).

Pressure and/or Content of Air

Thomas (1974) manipulated the pressure and content of the air in an operant-conditioning chamber by placing the lever-pressing apparatus inside a hyperbaric chamber. The breaking points of rats for which responding was maintained by food increased at air pressures slightly greater than normal in some conditions, but at the highest pressures studied, breaking points were invariably reduced. Increasing the proportion of helium in the air, however, greatly attenuated the break-point reductions produced by increased air pressure. In a second study, Thomas (1976) found that administration of *d*-amphetamine increased breaking points at mid-sized doses and decreased breaking points at larger doses; this function was shifted to the left in conditions with increased air pressure.

Brain Lesions

Assessing the effects of specific brain lesions on performance of animals on PR schedules of food delivery appears to have a great deal of potential use, especially as lesion-making techniques and related technologies continue to improve. Roberts et al. (1994) found that breaking points of rats were increased following lesions of the central serotonin system, whereas the breaking points of rats given sham surgeries were unaffected. A similar outcome was observed with other groups of rats responding on PR schedules of cocaine infusions, demonstrating that break-point increases induced by

these lesions were not specific to food-maintained behavior. Stewart and Blampied (1975), on the other hand, showed that neither dorsal nor ventral hippocampal lesions changed performance of rats on a geometrically increasing PR, relative to that of subjects that had received no operation.

Pre-Session Feeding, Response Effort, and Extinction

One would expect that feeding an experimental subject just before its daily session would disrupt subsequent performance. Skjoldager et al. (1993) demonstrated this effect using a between-groups design in which rats pressed a lever according to a PR schedule. They also found that pre-session feeding disrupted behavior maintained by larger reinforcers (more pellets) to the same extent as behavior maintained by smaller reinforcers. Similarly, if food presentations on the PR schedule were completely discontinued (i.e., extinction was arranged for lever pressing), persistence on the schedule was decreased in both groups in about the same manner. If the lever was made more difficult to press (by raising it high above the chamber floor), however, behavior maintained by the larger reinforcer was relatively less disrupted.

Timberlake (1984) showed that feeding rats after their daily experimental sessions did not alter PR performance unless such feedings were so delayed (23 hrs) that they amounted to pre-session feedings. Ferguson and Paule (1995), on the other hand, found that persistence on a PR schedule by rats was not affected by pre-session feeding. This outcome, however, may have depended more upon procedural eccentricities associated with this laboratory's experimental design than on some previously unsuspected limitation of basic behavioral principles; progressive-ratio performance was determined once per session in a fairly complex multiple-schedule context, and components lasted a maximum of 10 min.

Reinforcement-Schedule History

A few studies have used PR performance as an index of the influence of a subject's reinforcement history. In a between-subjects version of this general design, different groups of subjects would be exposed to different contingencies of reinforcement, after which all subjects would respond according to a PR schedule. Cohen et al. (1994) found no differences in stable PR performance between groups of pigeons previously exposed to FR, variable-ratio (VR), or differential-reinforcement-of-low-rate (DRL) schedules. Short-lived differences in performance, however, were observed across groups during the first few sessions of exposure to the PR schedule. Specifically, pigeons that had been exposed to VR or FR schedules generally responded more rapidly, exhibited shorter pre-ratio pauses, and generated higher breaking points during the first few sessions of PR-schedule exposure than did other subjects.

A similar outcome was demonstrated by Tatham and Wanchisen (1994), who used a within-subject design in which rats were exposed to a single PR "test" session following multiple sessions of exposure to a variable-interval (VI) schedule; the VI schedule value was changed following test sessions (e.g., from VI 15 s to VI 1 min). After a number of sessions at the new schedule value, another PR test session was conducted, and the pattern was repeated again (a total of five VI values were studied with each subject). In general, greater PR persistence (i.e., higher breaking points) was observed following experience with VI schedules arranging relatively high rates of reinforcement (and high rates of responding) than those arranging relatively low rates of reinforcement (and low rates of responding).

Alternative Response Options

The earliest work with PR schedules was carried out in a concurrent-schedule context (see History and General Characteristics of PR Responding section, above), and subsequent investigators have continued this tradition. Dardano and Sauerbrunn

(1964) arranged a circumstance nearly identical to Findley's initial experiments, in which pecks on one key produced food according to one of two PR 50 schedules, and responses on another key switched the schedule in effect and reset the ratio requirement to 50. In this experiment, however, every response in one of the two PR components produced a brief electric shock. The results indicated that as shock intensity increased, persistence on the shock-free PR also increased. Subsequent experiments reported by the same investigator showed that (a) if shocks were arranged for pecks on the reset key, but both PR components were shock-free, pigeons persisted longer in the PR components than if reset responses were not shocked (Dardano, 1968), (b) if pecks on one key produced food according to a PR schedule, and pecks on a second key produced time-outs from the session, rate of responding on the latter key increased as the ratio requirements became larger, with most pecks occurring during the pause following reinforcer delivery (Dardano, 1973), and (c) if three keys were available -- pecks on one produced food according to a PR 50 schedule, pecks on another reset the ratio and were shocked, and pecks on the third produced time-outs -- pigeons generally pecked the reset key more often than the time-out key, but as shock intensity increased, these frequencies reversed (Dardano, 1974). Using the simpler two-key procedure (pecks on one were reinforced according to a PR schedule and pecks on the other reset the ratio), Hurwitz and Harzem (1968) found a direct relation between PR step size and the probability of a switching response occurring after completion of a single ratio. In addition, they showed that as time in a 60-min session passed, the probability of switching after the completion of only one ratio first increased (peaking at about the halfway point) and then decreased.

Other investigators have used PR schedules to examine specifically whether subjects' response patterns in concurrent- or concurrent-chained schedules can be described as "optimal." That is, the question is whether response patterns in these

situations minimize costs (i.e., responses) and maximize benefits (i.e., reinforcers per unit time). A procedure developed by Hodos and Trumble (1967) has served as a useful tool in addressing this issue (e.g., Mazur & Vaughan, 1987; Wanchisen et al., 1988). In this method, chimpanzees chose between a PR schedule and an FR schedule, the completion of which, in some conditions, produced food and reset the PR to its minimum value. As a general rule, a typical subject's behavior appears to be sensitive to costs and benefits accruing across extended periods of time, but this sensitivity does not necessarily translate into optimal performance. For example, Wanchisen et al. (1988) found that during conditions in which selection of the FR schedule did not reset the PR response requirement, pigeons tended to choose the PR option repeatedly across trials until the response requirement was about equal to, or slightly greater than, the FR. During conditions in which selection of the FR option reset the PR response requirement to its minimum value, pigeons tended to select the PR option a number of times, after which they switched to the FR option – well before the PR response requirement equaled the FR requirement. Both of these patterns of responding (i.e., in the "no-reset" and the "reset" conditions) approached optimality, in terms of responses emitted per reinforcer earned, but, in most cases, reliable deviations from optimal performance have been observed. As an aside, these deviations have generated some debate as to whether choices in these procedures are directly controlled by overall ratios of costs to benefits or by other factors (Mazur & Vaughan, 1987).

Drug-Maintained PR Responding

The use of PR schedule performance as a index of reinforcer efficacy and/or subject motivation has blossomed fairly spectacularly in the study of self-administration of drugs. Beginning with demonstrations that drug infusions could function as reinforcers in FR schedules of delivery (e.g., Pickens & Thompson, 1968), this line of research has evolved into a coherent discipline using PR schedules of drug

administration to address two major clusters of experimental questions (with considerable overlap across categories). First, some reports have continued to be concerned with whether a particular compound can reinforce behavior (e.g., Bedford, Bailey, & Wilson, 1978; French, 1994), or are designed to compare the reinforcing efficacy of different drugs in a particular context (e.g., Brady & Griffiths, 1976; Carroll, Krattiger, Gieske, & Sadoff, 1990; French, Lopez, Peper, Kamenka, & Roberts, 1995; Griffiths, Brady, & Snell, 1978; Hoffmeister, 1979; Kantak, Lawley, Wasserman, & Bourg, 1991; Risner & Cone, 1986; Risner & Silcox, 1981; Winger & Woods, 1985). Second, a host of investigators have attempted to characterize the influence of a wide range of other variables on behavior maintained by PR schedules of drug administration (e.g., Depoortere, Li, Lane, & Emmett-Oglesby, 1993; Lacosta & Roberts, 1993; Li, Depoortere, & Emmett-Oglesby, 1994; Loh, Fitch, Vickers, & Roberts, 1992; Loh & Roberts, 1990; McGregor, Baker, & Roberts, 1994; McGregor, Lacosta, & Roberts, 1993; McGregor & Roberts, 1993; McGregor & Roberts, 1995; Richardson & Roberts, 1991; Richardson, Smith, & Roberts, 1994; Ritz, Garcia, Protz, Rael, & George, 1994; Roberts & Bennett, 1993; Roberts, Bennett, & Vickers, 1989; Roberts, Loh, & Vickers, 1989; Willner, Hardman, & Eaton, 1995). These two lines of experimentation will be discussed briefly in the following sections.

As with behavior maintained by PR schedules of food delivery, general conclusions based upon across-study comparisons in this area must be tempered somewhat by the significant differences in procedures employed by various laboratories; the term "progressive ratio" has been used to describe vastly different contingencies of reinforcement. For instance, several early experiments (e.g., Brady & Griffiths, 1976) arranged a procedure in which response requirements increased across days, rather than from one reinforcer delivery to the next, and described these contingencies as a PR schedule. Other studies have included rather lengthy time-outs

following reinforcer deliveries (e.g., Carroll et al., 1990; Griffiths, Bradford, & Brady, 1979; Winger & Woods, 1985). A number of reports have dispensed with break-point criteria by programming sessions to end after a fixed period of time (e.g., Roberts et al., 1989) or have based break-point criteria on the number of infusions received per day in a situation in which the absolute number of infusions possible per day was limited by the experimenter (e.g., Brady & Griffiths, 1976; Griffiths et al., 1979; Griffiths et al., 1978; Hoffmeister, 1979; Risner & Cone, 1986; Risner & Silcox, 1981). And almost every study concerned with drug-maintained behavior has employed PR schedules with geometrically increasing response requirements (or some variant of a geometric progression), rather than the arithmetic progressions more commonly used in experiments investigating food-maintained PR performance. It may be encouraging to note that in recent years these procedural details have varied less widely across different laboratories. One would hope that this trend will lead to a situation in which data generated in different laboratories concerned with PR schedules of drug delivery can be compared and integrated into interpretable generalizations.

Identifying the Reinforcing Efficacy of Drugs

Determining whether a particular drug functions as a reinforcer can be accomplished the same way one would establish any other event as a reinforcer: If contingent application of the drug results in an increased frequency of the drug-producing response, then, in that circumstance, the drug serves a reinforcing function. When using PR schedules to answer this question, one must determine that the breaking-point maintained by contingent application of a drug is greater than that observed for contingent application of a "neutral" event, such as administration of a saline solution. Few experiments have included control conditions in which breaking points associated with saline infusions were determined; most investigators have been satisfied to demonstrate that drug infusions maintain breaking points significantly

greater than zero. This strategy rests on the belief that drug infusions do not generally elicit considerable rates of lever pressing. Although the inclusion of appropriate control conditions would be more convincing, almost all cumulative records of responding generated by contingent drug infusions have strongly resembled patterns produced by PR schedules of food delivery (e.g., Brady & Griffiths, 1976; Carroll et al., 1990; French, 1994; French et al., 1995; Griffiths et al., 1979; Griffiths et al., 1978; Loh et al., 1992; Loh & Roberts, 1990; McGregor et al., 1994; McGregor & Roberts, 1993; Risner & Cone, 1986; Roberts, Bennett, & Vickers, 1989; Roberts, Loh, & Vickers, 1989; Willner et al., 1995), providing some evidence that infusions of certain drugs serve as reinforcers, rather than elicitors, of the drug-producing behavior.

Reports in this area have been designed to compare (a) the breaking points maintained by two or more different drugs and/or (b) the breaking points maintained by two or more doses of the same drug. In an early study, Brady and Griffiths (1976) showed that breaking points maintained by cocaine infusions were significantly higher than those for methylphenidate or secobarbital. Others have shown that larger doses of a reinforcing drug (cocaine, for example) support higher breaking points than smaller doses, although the increasing function has been observed to plateau or decrease at the highest doses tested (e.g., Bedford et al., 1978; Griffiths et al., 1979). Comparisons of the reinforcing efficacies of drugs have been conducted within and across pharmacological classes, including opiates (e.g., Hoffmeister, 1979), stimulants (e.g., Carroll et al., 1990; Griffiths et al., 1978; Kantak et al., 1991; Risner & Cone, 1986; Risner & Silcox, 1981; Winger & Woods, 1985), and hallucinogens (e.g., French, 1994; French et al., 1995). In some reports, the relative reinforcing efficacy of the tested drugs, as indexed by PR performance, has correlated well with the relative abuse potential of the drugs among human users (e.g., Griffiths et al., 1978).

Drug-Maintained PR Performance as a Baseline

The drug-self-administration literature has grown at a phenomenal rate. A sizable proportion of these reports has utilized performance on PR schedules of drug delivery as a baseline against which the effects of other variables may be assessed. These other variables have included administration of a second drug (e.g., Depoortere et al., 1993; Lacosta & Roberts, 1992; Loh et al., 1992; McGregor et al., 1993; McGregor & Roberts, 1993; McGregor & Roberts, 1995; Richardson & Roberts, 1991; Richardson et al., 1994; Roberts & Bennett, 1993; Roberts, Loh, & Vickers, 1989), the stage of estrous in rats (e.g., Roberts, Bennett, & Vickers, 1989), lesions of the brain (Loh & Roberts, 1990; McGregor et al., 1994; Roberts et al., 1994), repeated response-independent exposure to the self-administered drug (e.g., Li et al., 1994), and subjects' state of deprivation (Willner et al., 1995). A more detailed description of these topics is not directly relevant to the present experiment and will not be attempted here.

The Present Study

Taken as a whole, the foregoing sections suggest that PR schedules have found a welcome home in the experimental psychologist's toolbox. It seems clear that a majority of investigators currently make use of this tool by treating the behavioral patterns maintained by PR schedules as baselines upon which other variables may be applied. But as with any procedure, drug, or device developed as a result of the activities of a group of scientists, a lack of knowledge concerning the fundamental manner in which the tool operates can be costly to users. For instance, when judging the reinforcing efficacy of different drugs, it would be helpful to know whether the conclusion (e.g., drug A supports a higher breaking point than drug B) is dependent upon specific details of the procedure, such as the step size or break-point criterion used. One could imagine a circumstance in which one reinforcer was more efficacious

than another only when both were cheaply acquired; in another context (e.g., when both are difficult to obtain), the relative strength of the two reinforcers could change. In fact, an outcome much like this has been reported by Hursh (1984). He found that when concurrent VI schedules arranged reinforcer deliveries relatively frequently, rats pressed more rapidly on a lever to produce electrical brain stimulation (EBS) than on a lever to produce food; when concurrent VI-schedule values were longer, pressing rates were higher on the lever producing food than on the lever producing EBS.

The present experiment was designed to provide a detailed description of the effects of step size and break-point criteria on keypecking by pigeons on an arithmetically increasing PR schedule of food delivery. The general procedure consisted of holding the break-point criterion constant while varying the step size in an ascending series across conditions. Each step-size condition was continued until response patterns were judged to be stable (the stability criteria will be described fully below). In Part 1, two ascending series of step sizes were studied for each subject with the break-point criterion held constant at 5 min (i.e., sessions ended when 5 min elapsed in which no keypecks were recorded); in Part 2, a single ascending series of step sizes was studied for each subject with the break-point criterion fixed at 15 min. Unlike the outcome reported by Hodos and Kalman (1963), data from the present experiment suggest that breaking points on arithmetically increasing PR schedules of food delivery are generally unaffected by step-size value. In general, the average number of completed ratios in each condition was found to vary in an orderly fashion with changes in step size and break-point criterion, and a mathematical function that described these data well was proposed and evaluated.

METHOD

Subjects

Seven adult White Carneau pigeons (*Columba livia*) of indeterminate sex served. Each bird had prior experience with experimental procedures; four of the seven (Subjects 2243, 3858, 3883, and 3888) had previously pecked response keys in an experiment investigating effects of cocaine on a multiple PR FR baseline, whereas the remaining three (Subjects 5615, 5642, and 5775) had been exposed to a variety of operant contingencies in an undergraduate laboratory course. The pigeons were housed individually in a colony room (16:8 hr light/dark cycle) with free access to water and grit. They were maintained at 80% of free-feeding body weight via post-session supplemental feedings, when necessary.

Apparatus

An operant conditioning chamber for pigeons, measuring 31 cm long by 35 cm deep by 35 cm high was used. Three translucent response keys were mounted horizontally, 25 cm above the floor, behind 2.5-cm holes cut through the front wall. The keys were 8.5 cm apart, center to center, and could be illuminated from behind with colored lights. Only the center key and a red keylight were used in this experiment. A minimum static force of 0.15 N on the response key was required to register a response. A 1.1-W DC lamp (houcelight) that provided low-level illumination was located above the center key and 3 cm below the ceiling. Centered 13 cm below the row of response keys was a rectangular opening through which the pigeon could gain access to mixed grain during a 5-s period when a hopper was raised. The feeder opening was illuminated and the keylights and houcelight were darkened

when the hopper was raised. Extraneous sounds were masked by white noise (95 dB), provided by a wall-mounted speaker in the room housing the conditioning chamber, and by a ventilating fan. An IBM-compatible computer located in an adjacent room arranged experimental events and collected data via the ECBasic control system (Walter & Palya, 1984), while a Gerbrands cumulative recorder produced on-line records of responding.

Procedure

One session was conducted per day, per subject, seven days per week. Each session was preceded by a 5-min blackout period in which pecks were not recorded and food was not available. Pecking the center key was maintained by an arithmetic PR schedule of food delivery, with the increment size varying across conditions. Three stability criteria were used to determine condition changes. First, each condition continued for at least 25 sessions. Second, a condition was not changed unless behavior appeared stable according to visual inspection of daily breaking-point plots and cumulative records of responding. Third, a condition was continued until no breaking point observed during the final 10 sessions of a condition fell outside of the previously observed range for that condition. In general, increment sizes were increased from one condition to the next, until a step size that maintained very little responding was reached, after which the increment size was reduced to a relatively small value and the process was repeated.

Part 1

The break-point criterion was held constant at five min during Part 1 (i.e., a session ended when five min elapsed without a peck). Table 1 shows the sequence of conditions and the number of sessions conducted during each for each subject in Part 1.

Part 2

For each subject, Part 2 began immediately following the last session of Part 1 (except for Subjects 5642 and 5775, which did not participate in Part 2). The break-point criterion was held constant at 15 min during Part 2, and, as in Part 1, the magnitude of the PR step size was systematically altered across conditions. Table 2 shows the sequence of conditions and the number of sessions conducted during each for every subject in Part 2.

TABLE 2
STEP SIZES (AND NUMBER OF SESSIONS IN EACH CONDITION) FOR
SUBJECTS IN PART 2

Condition	2243	3858	Subject 3883	3888	5615
1.	3 (15 ^a)	3 (65)	3 (9 ^a)	3 (51)	3 (30)
2.	8 (45)	8 (46)	8 (29)	8 (40)	8 (39)
3.	15 (33)	15 (47)	15 (26)	15 (40)	15 (35)
4.	30 (26)	30 (28)	30 (27)	30 (80)	30 (26)
5.	60 (42)	60 (32)	60 (39)	60 (47)	60 (39)
6.	-----	5 (26)	120(41)	120(43)	5 (29)
7.	-----	-----	240(27)	5 (37)	-----

^aCondition was terminated before keypecking met the stability criteria. Hence, data from these conditions are not included in the present analysis.

RESULTS

Breaking Points

All figures presented in this and every following section show data taken from the final 10 sessions in each condition (i.e., the stable block of sessions). Figures 1 and 2 show average breaking points as a function of step size for each pigeon in Parts 1 and 2, respectively. Note that the horizontal axes are scaled logarithmically and identically across subjects, whereas the vertical axes are all scaled linearly, but the absolute ranges are different for each subject. Figure 1 shows that average breaking points generally remained fairly constant (Subjects 2243, 3858, 3883, 3888, and 5775) or increased (Subjects 5615 and 5642) across a range of step-size values with the break-point criterion fixed at five min during the first ascending series of step sizes. Subject 3858's breaking points, for example, were confined between approximately 42 and 64 responses across step sizes ranging from three to 80 responses, with no obvious trend related to step-size magnitude. Subject 5642's breaking points, on the other hand, increased from around 83 responses at a step size of three to approximately 384 responses at a step size of 160.

Replications of conditions generally produced similar average breaking points; in two cases (Subject 3858 at a step size of 3 and Subject 3883 at a step size of 40), replications resulted in almost identical average breaking points as the original conditions. For most subjects, the second ascending series of step sizes resulted in effects quite similar to those of the first series. For both subjects whose break points increased across larger step-size values (5615 and 5642), however, the second sequence of increasing step-size conditions produced a relatively flatter break-point function than

Figure 1. Mean breaking points as a function of PR step size for each subject in Part 1. Filled points correspond to the first sequence of increasing step sizes and open points refer to the second sequence, open triangles correspond to direct replications of a specific step size, and error bars represent standard deviations from the mean. Note that the horizontal axis is scaled logarithmically.

5-min break-point criterion

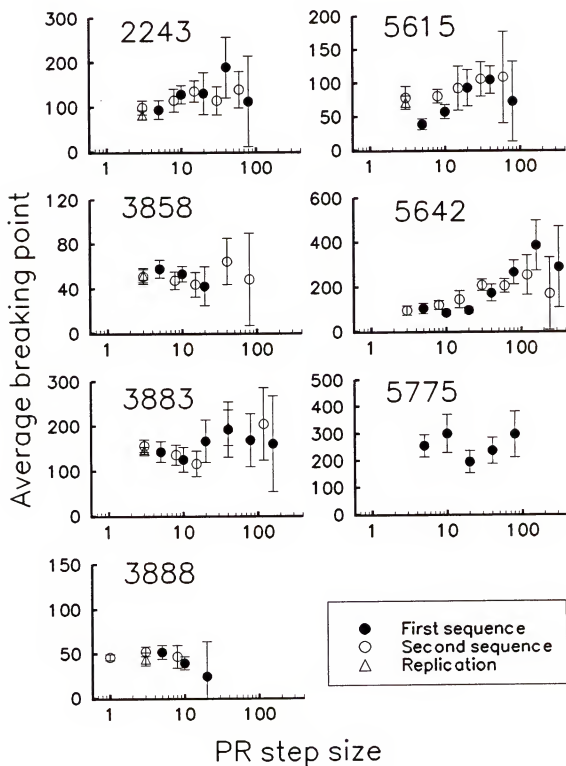
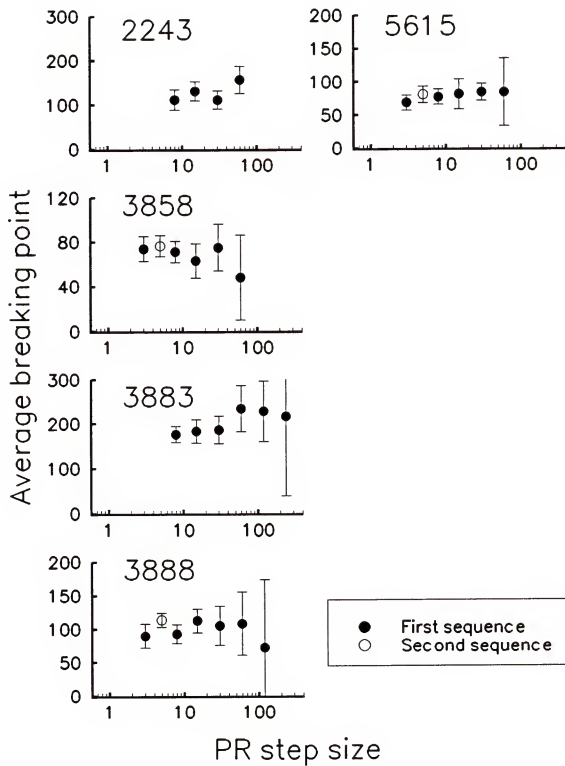


Figure 2. Mean breaking points as a function of PR step size for each subject in Part 2. Plotting conventions are the same as in Figure 1.

15-min break-point criterion



did the first sequence. For Subject 5642, this flattening was a consequence of reduced breaking points at larger step sizes during the second sequence of conditions, whereas for Subject 5615, break points at small step sizes increased relative to those observed during the first sequence.

Figure 2 shows that average breaking points were relatively constant across step sizes for each subject with the break-point criterion fixed at 15 min. For example, Subject 5615's breaking points ranged from about 68 responses at a step of 3 to approximately 84 responses at step size of 30. Any increases in average breaking point observed across increasing step sizes were slight; the standard deviations associated with the highest and the lowest average break-points overlapped for every subject. The overall mean breaking point (averaged across step sizes) in Part 2 was higher than that observed in Part 1 for four of five subjects (not 5615). The increases ranged from 5.83 (Subject 2243) to 55.83 (Subject 3888) responses, whereas Subject 5615's overall mean breaking point declined by 2.38 responses.

Number of Ratios Completed

Figures 3 and 4 show the average number of completed ratios as a function of step size in log-log coordinates for each subject in Parts 1 and 2, respectively. Note that the average number of completed ratios for a particular condition is directly proportional to the corresponding breaking point shown in Figures 1 and 2 (i.e., the number of completed ratios in a particular condition can be obtained by dividing the average breaking point by the corresponding step size). Figure 3 shows that, for every subject, the average number of ratios completed decreased across increasing step sizes. Furthermore, the function appears strikingly linear in these coordinates for all subjects. The dashed lines represent the best-fitting power functions of the form $y = b * x^a$.

Table 3 shows the values of both free parameters a and b for each subject and the proportion of variance accounted for by the best-fitting power functions. Best-fitting

Figure 3. Average number of completed ratios as a function of PR step size for each subject in Part 1. The dashed lines show the best-fitting functions for each subject's data. Note that both axes are scaled logarithmically.

5-min break-point criterion

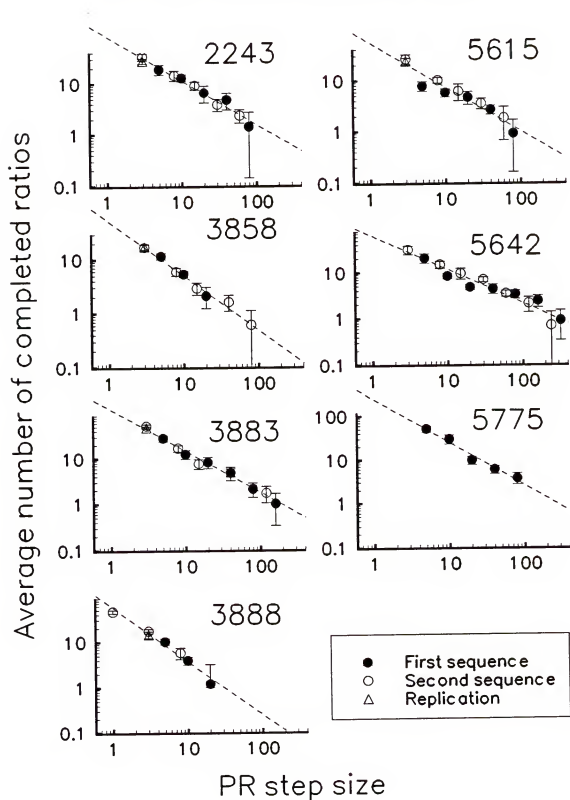
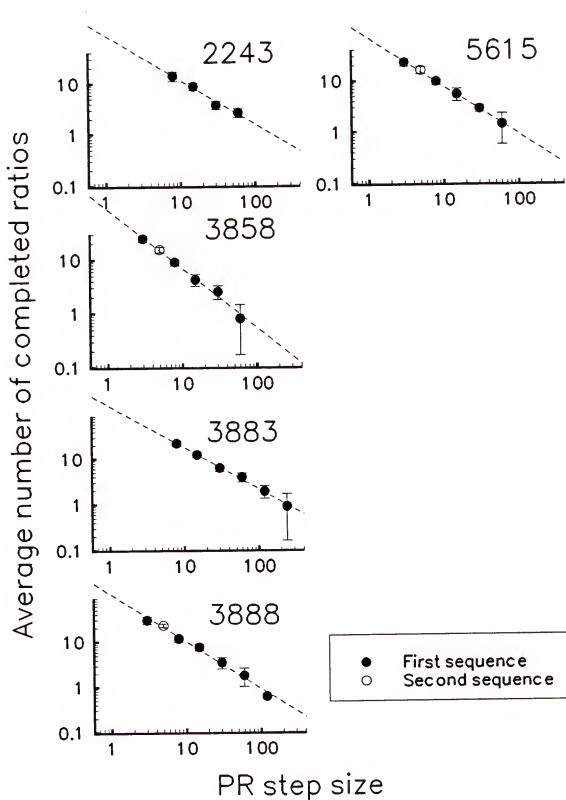


Figure 4. Average number of completed ratios as a function of PR step size for each subject in Part 2. The dashed lines show the best-fitting functions for each subject's data. Note that both axes are scaled logarithmically.

15-min break-point criterion



functions were determined on logarithmically transformed data via the conventional least-squares method. In Part 1 (top panel), the parameter a , which represents the slope of this function in log-log coordinates, was slightly less than, or about equal to -1; when a equals -1, the function relating breaking point to step size appears absolutely flat. The parameter b , on the other hand, refers to vertical displacements of the fitted curves in log-log coordinates, with larger b values shifting a function upward. This parameter varied across subjects, ranging from 51.41 (Subject 3858) to 245.17 (Subject 5775). Translated into PR performance, a function with a larger b value is correlated with a greater number of ratios completed (and greater breaking points) at all step sizes, compared with a function with a smaller b value (given equivalent values of a). The best-fitting power functions accounted for most of the variance in each subject's data, with R^2 values ranging from .91 (Subject 5615) to .99 (Subjects 3858, 3883, and 3888).

Figure 4 and Table 3 indicate that the relation between average number of completed ratios and step size in Part 2 was generally quite similar to that observed during Part 1. Average number of completed ratios decreased across increasing step sizes, and the declines appear strikingly linear in log-log coordinates. Table 3 (bottom panel) shows that values of a were again clustered around -1, whereas b values ranged from 68.60 (Subject 5615) to 150.02 (Subject 3883). Parameter values of a were generally fairly similar across Parts 1 and 2 within individual subjects. The values of parameter b , however, were larger in Part 2 than in Part 1 for each subject, although some increases were very small (e.g., an increase of 1.11 for Subject 2243). Thus, increasing the break-point criterion from five to 15 min appeared to have little effect on the slope of the function relating average number of completed ratios to step size, but the function was generally shifted upward slightly with the longer break-point criterion. As in Part 1, best-fitting power functions accounted for most of the variability in each subject's data (R^2 ranged from .97 to 1.00).

TABLE 3
 PARAMETER VALUES AND PROPORTION OF VARIANCE ACCOUNTED FOR
 BY THE BEST-FITTING FUNCTIONS BETWEEN AVERAGE NUMBER OF
 COMPLETED RATIOS AND STEP SIZE IN PARTS 1 AND 2 FOR EACH SUBJECT

Subject	Part 1		R ²
	a	b	
2243	-0.87	84.20	.98
3858	-1.01	51.41	.99
3883	-0.92	125.30	.99
3888	-0.87	52.66	.99
5615	-0.86	53.28	.91
5642	-0.73	62.95	.97
5775	-0.99	245.17	.98

Subject	Part 2		R ²
	a	b	
2243	-0.87	85.31	.99
3858	-1.11	89.20	1.00
3883	-0.92	150.02	1.00
3888	-1.04	110.02	.97
5615	-0.94	68.60	.99

Total Number of Responses

Figures 5 and 6 show the average total number of responses per session as a function of step size for each pigeon in Parts 1 and 2, respectively. Note that both axes are scaled logarithmically. For all subjects, the average total number of responses decreased across increasing step sizes in both Parts 1 and 2. Figure 5 shows that the nature of these declines varied across subjects in Part 1, with some functions appearing more curvilinear than others. In addition, Figure 5 highlights the differences in performances observed for some subjects across the first and second sequences of increasing step-size conditions, which was noted previously (see Breaking-Point section, above). For example, the average total number of responses emitted by Subject 5615 across the first sequence of step sizes increased slightly and then decreased; in the second sequence, the function began at a much higher level and only decreased with increasing step sizes. Figure 6 shows that in Part 2 the total number of responses emitted by each subject declined with increasing step sizes. These declines were generally more orderly than in Part 1, and there were no major differences across subjects.

Cumulative Records of Keypecking

Figure 7 shows two cumulative response records of keypecking that illustrate some dynamic features of performance of two subjects on the progressive-ratio schedules of food delivery. Other subjects' cumulative records did not differ in fundamental ways from those shown here. The top panel shows a record of keypecking generated by Subject 5615 during Part 1 on a PR 15 schedule, and the bottom panel presents data from Subject 2243 during Part 1 on a PR 60 schedule. Both panels show the "break and run" pattern of responding characteristic of FR schedules of reinforcement (cf. Ferster & Skinner, 1957), in which a period of little or no responding is followed by rapid and sustained bursts of keypecking. Responding appeared to become a bit more erratic as the number of responses required for food increased (e.g.,

Figure 5. Average total responses per session as a function of PR step size for each subject in Part 1. Note that both axes are scaled logarithmically. Other plotting conventions are the same as in Figure 1.

5-min break-point criterion

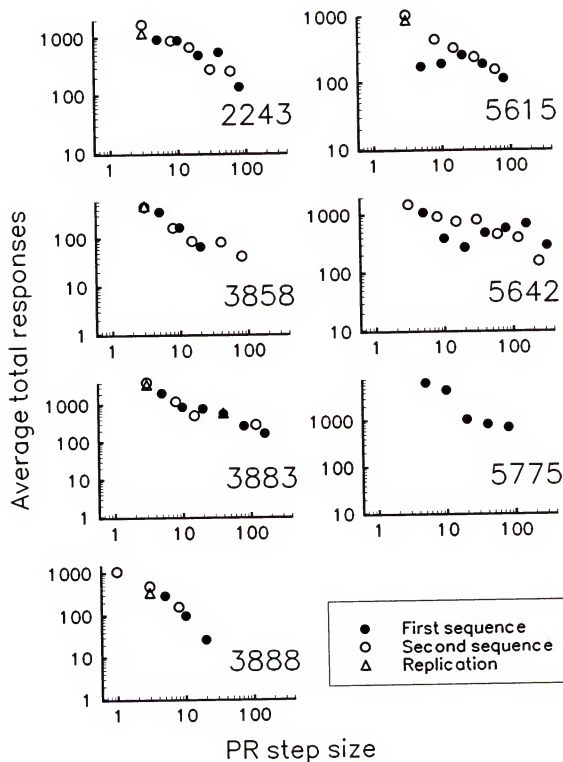


Figure 6. Average total responses per session is shown as a function of PR step size for each subject in Part 2. Plotting conventions are the same as in Figure 5.

15-min break-point criterion

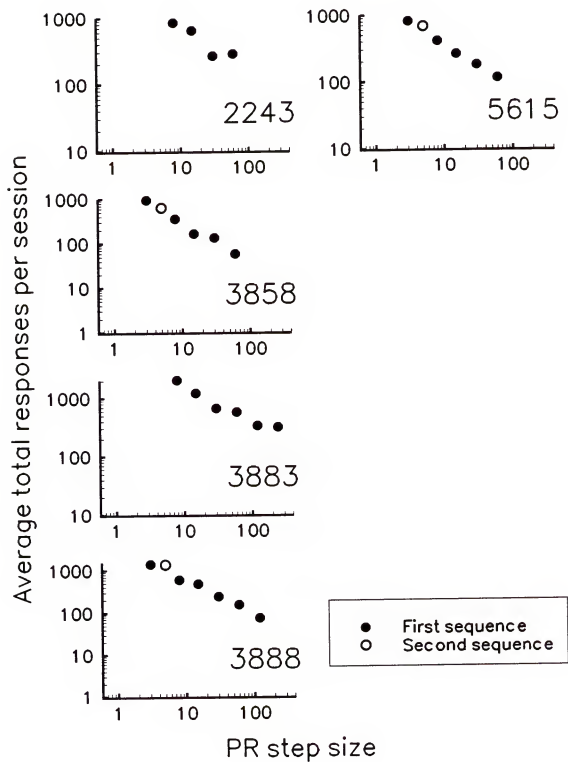
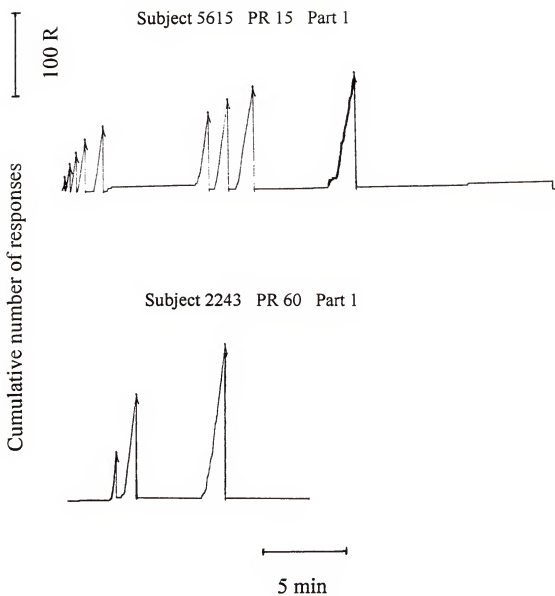


Figure 7. Cumulative response records of keypecking for Subject 5615 responding on a PR 15 schedule in Part 1, and for Subject 2243 responding on a PR 60 schedule in Part 1. Continuous passage of time in a session is shown on the horizontal axis; the vertical axis shows cumulative number of keypecks. The pen was deflected briefly and reset to the baseline after each food presentation.



for Subject 5615, compare the smooth records of keypecking during the small ratios occurring early in the sequence with the record of keypecking during the final ratio, which includes several short periods of pausing during the ratio run). The length of pre-ratio pauses was not steady from ratio to ratio; instead, pauses appeared to increase, in general, as the session continued. The increases in pause durations shown in both panels of Figure 7, however, do not appear constant from one ratio to the next (i.e., pause durations do not, for example, double with each successive ratio). The next section provides a more detailed description of relations between pre-ratio pausing and progressively increasing ratio requirements.

Pre-Ratio Pauses

Figures 8, 9, and 10 show pre-ratio-pause durations as a function of position in the PR for Subjects 5615, 3858, and 5642, respectively (Figures 8 and 10 show data recorded during Part 1, whereas Figure 9 shows data recorded during Part 2). These figures illustrate the typical patterns of pausing observed in every subject. Pauses were defined as the time between reinforcer delivery (or, for the first ratio, the start of the session) and the first response in the following ratio; if a session was completed with no responses in the final ratio, the pre-ratio pause was scored as equal to the break-point criterion (i.e., five min in Part 1, 15 min in Part 2). Data are presented from the first (filled circles) and last (open circles) session of the 10-session block meeting the stability criteria in each condition, and individual panels correspond with each step-size condition.

Figure 8 shows that for Subject 5615 in Part 1, at small step sizes, pre-ratio-pause durations tended to remain relatively short across numerous progressively increasing ratio requirements, after which longer pauses abruptly occurred. For example, in the initial PR 3 condition (upper left-hand panel) pre-ratio pauses were brief for 20-25 ratios, after which pause durations abruptly increased. On a PR 8 schedule, pauses remained short for approximately 10-12 ratios, after which pause durations abruptly

increased. Further increases in step size resulted in fewer and fewer ratios in the initial short-pause-duration period. The sudden increase in pause durations, however, was observed at every step size. Figure 9 shows a similar overall pattern in Part 2 for Subject 3858. Pause durations generally remained short across a number of ratios, after which longer pause durations were abruptly apparent. Larger step sizes resulted in this abrupt increase taking place sooner in the progression. In general, there were no major differences between patterns of pre-ratio pausing observed across Parts 1 and 2 for any subject.

Figure 10 shows pre-ratio pause data for Subject 5642 in Part 1. These data may be considered particularly interesting because this pigeon's breaking-point data during the first ascending series differed from those of the other subjects, as noted above (i.e., for this subject, breaking points generally increased with larger step sizes). It might be possible that this subject's pattern of pausing, in addition to the average breaking point it reached, would differ from other subjects'. Figure 10, however, indicates that Subject 5642's overall pattern of pausing was very similar to that observed with every other subject. Pause durations were short across several ratios with increasing response requirements, longer pause durations appeared abruptly, and larger step sizes shifted this function to the left. The only major difference between this subject's pattern of pre-ratio pausing and that observed in other subjects was that larger step sizes appeared to shorten the initial brief-pause-duration period to a lesser extent.

Figure 8. Pre-ratio pauses as a function of position in the PR for Subject 5615 in Part 1. Filled circles correspond with the first, and open circles with the last, session of the 10-session block meeting the stability criteria for each step-size condition.

5-min break-point criterion

5615

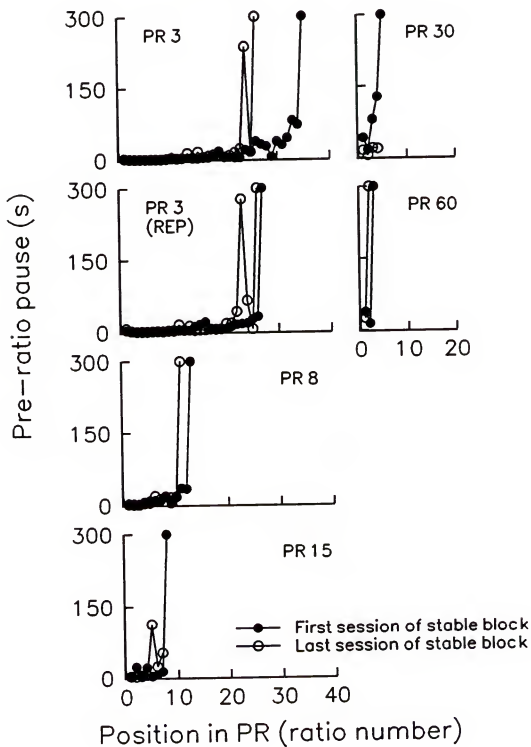


Figure 9. Pre-ratio pauses as a function of position in the PR for Subject 3858 in Part 2. Filled circles correspond with the first, and open circles with the last, session of the 10-session block meeting the stability criteria for each step-size condition.

15-min break-point criterion

3858

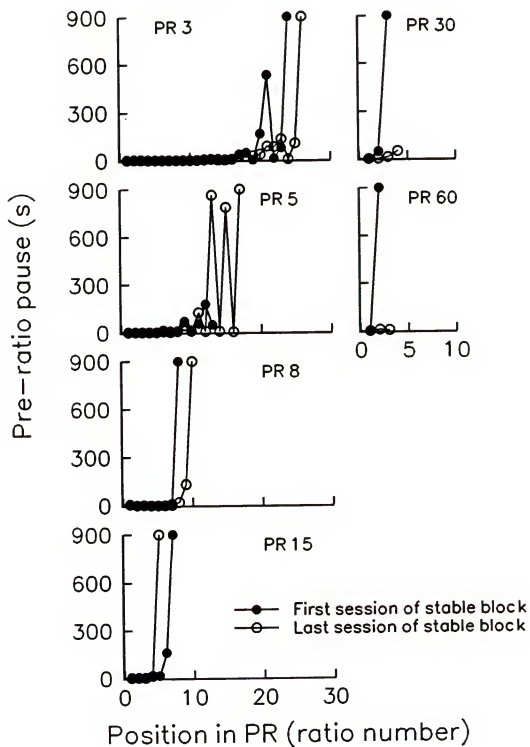
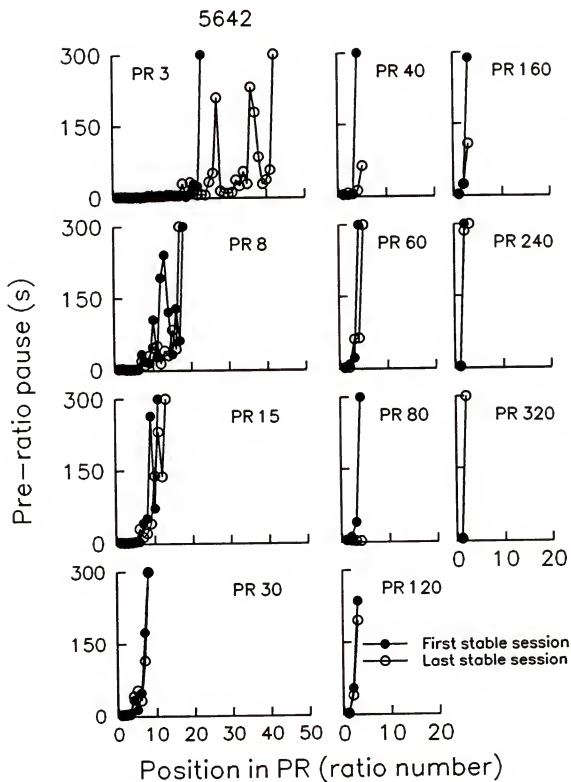


Figure 10. Pre-ratio pauses as a function of position in the PR for Subject 5642 in Part 1. Filled circles correspond with the first, and open circles with the last, session of the 10-session block meeting the stability criteria for each step-size condition.

5-min break-point criterion



DISCUSSION

The results of this experiment replicated several aspects of PR performance that have been described in previous reports, but differed from the existing literature in other respects. In line with the findings of numerous laboratories (e.g., Baron et al., 1992; Findley, 1958; Thomas, 1974), cumulative records of responding on PR schedules of food delivery appeared similar to the "break-and-run" performance commonly observed on FR schedules (e.g., Ferster & Skinner, 1957), with bouts of rapid and sustained keypecking preceded by periods in which no pecking was observed. The duration of this period of pausing was an orderly function of both (a) the current requirements of the PR schedule (i.e., position in the progression) and (b) step-size magnitude (see Figures 8 through 10), a finding that replicates and extends upon previous research (e.g., Baron et al., 1992).

For the most part, the present data set indicates that step-size magnitude did not substantially influence breaking points. This was clearly the case for six of seven subjects (not 5642) after an exhaustive examination of the step-size dimension with the break-point criterion fixed at 5 min (Part 1); when the break-point criterion was fixed at 15 min (Part 2), the results were consistent across all five subjects. This outcome represents the most extreme departure from previous reports, in which breaking points have been observed to increase as a function of step-size magnitude (e.g., Hodos & Kalman, 1963). The procedures employed by the present study and this predecessor, it may be noted, differed in numerous ways, including the species of subject studied, the response required, the reinforcement and drug-administration history of the subjects,

the form of the reinforcer, and the length of exposure to each step-size condition, among other differences.

The length of exposure to each step-size condition, in particular, may have played a significant role in determining the form of the relation between step-size magnitude and average breaking point. In this experiment, each step-size condition remained in effect until performance stabilized (range: 25 to 94 sessions). In contrast, Hodos and Kalman's (1963) procedure arranged for only six sessions of exposure to a particular step size, with successive conditions arranging larger step sizes. Although the stable breaking points (i.e., the last 10 sessions in a condition) did not differ markedly across step-size conditions within individual subjects in the present experiment, short-term alterations in breaking point were commonly observed in transitions between step-size conditions. More specifically, when step sizes were increased from one condition to the next, breaking points often increased temporarily as well. In Part 1, the breaking point observed in the first session of a new, larger step-size condition was greater than the average breaking point from the last 10 sessions in the smaller step-size condition in 90.4% of these condition transitions (individual-subject range: 75% to 100%); in Part 2, this occurred in 95.5% of these transitions (individual-subject range: 75% to 100%). Hence, had subjects in this experiment been exposed to fewer sessions in each condition, the breaking-point data may have more closely resembled Hodos and Kalman's (1963) results, but those data could not have been considered representative of stable performance in these circumstances.

The present study also showed that, in addition to the average breaking point, other characteristics of PR performance (e.g., the average total number of responses per session and the average number of completed ratios per session) varied in a predictable fashion with manipulations of basic PR-schedule variables (see Figures 3 through 6). These findings partially answer calls made for a broader description of

behavior maintained by PR schedules (e.g. Stewart, 1975). In fact, the effects of both step size and break-point criteria were quantified most satisfactorily with reference to the average number of ratios completed per session, rather than with reference to the average breaking points (a similar conclusion has been reached, for different reasons, by investigators studying drug self-administration, e.g., Loh & Roberts, 1990; Depoortere et al., 1993). Specifically, a power function with two free parameters (i.e., $y = b * x^a$) provided an excellent fit to each subject's data.

Not only did the functions relating average number of completed ratios per session to step size decrease in an orderly fashion for all subjects, but the values of the free parameters defining the best-fitting functions were fairly similar across subjects. The values of the parameter a , representing the slope of each function in log-log coordinates, were generally clustered around -1, and changing the break-point criterion from five to 15 min did not significantly alter these values (see Table 3). In terms of PR performance, if a were exactly equal to -1, an increase in step size would result in (a) no change in averaging breaking point, and (b) a directly proportional reduction in the average number of completed ratios observed. For example, doubling the step size would decrease the number of completed ratios by one-half. Alternatively, any decrease in step size, if a equaled -1, would result in (a) no change in average breaking point, and (b) a proportional increase in the average number of completed ratios (e.g., halving the step size would double the number of completed ratios). If values of a were observed to be greater than -1 (i.e., tending toward zero), alterations in the step size would result in a less-than-directly-proportional reduction in average number of ratios completed (e.g., doubling the step size might decrease the average number of completed ratios by one-third; hence, average breaking points would increase across larger step sizes). Alternatively, if values of a were less than -1, changes in step size

would lead to greater-than-directly-proportional alterations in PR performance (in this case, average breaking points would decrease across increasing step sizes).

The parameter b , on the other hand, varied more widely across subjects (range: 51.41 to 245.17), but was shown to be sensitive to changes in the break-point criterion. Specifically, "b" values in Part 2 were higher for each subject, (range of increases: 1.11 to 57.36). In terms of PR performance, values of "b" represent the average number of ratios expected to be completed at a step size of one (this is true only if a is equal to -1). Increasing the break-point criterion from five to 15 min, therefore, produced upward shifts of the function relating average number of completed ratios (and, concomitantly, average breaking point) to step-size magnitude, whereas the slope of this function remained relatively constant.

If the predictable and quantifiable relation between step size and average number of completed ratios observed in the present experiment could be replicated in other laboratories, the relation itself might serve as a useful tool. That is, research programs designed to assess the effects of other variables on PR performance could (a) demonstrate this functional relation as a baseline condition and then (b) apply other variables across several step-size conditions. The values of parameters a and/or b observed during treatment conditions, relative to the values observed during baseline, could be considered indices of a variable's effect. For example, acute or chronic administration of a drug might reduce the average number of completed ratios in equal proportions across all step sizes. In this case, a would be unchanged (since the function's slope would remain constant), but b would be reduced (i.e., the predicted number of ratios completed at a step size of one would be lower). Alternatively, drug administration might decrease the number of completed ratios at small step sizes while having no effect at larger step sizes, which would reduce the values of both a and b (i.e, in this case, both the slope and the vertical displacement would be lowered). Or, in

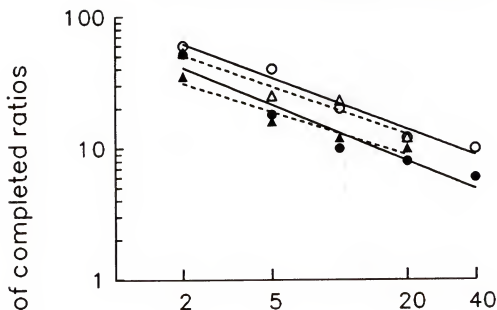
another case, exposure to a drug might increase the number of completed ratios only at large step sizes, which would reduce the value of a while leaving b unaffected (i.e., only the slope of the function would be reduced). Whatever the case, determining whether different classes of treatment conditions (e.g., drug administration, brain lesions, reinforcement history, reinforcer magnitude, etc.) differentially affect parameters a and b could function as a first step in the construction of general statements summarizing the relations between PR performance and a wide range of independent variables.

Although the examples conceived above remain speculative, these outcomes (as well as several other possibilities not specifically outlined) do not appear to stretch the imagination. Before the present analytic method could function as a baseline for other experimental questions, however, it is necessary to demonstrate that this basic relation between step size and average number of completed ratios holds in other laboratories. Fortunately, it is possible to analyze retrospectively data from previous reports to determine whether their data correspond or conflict with the present results. To this end, the average numbers of ratios completed across different step-size conditions were estimated from figures presented in Hodos and Kalman (1963) and Thomas (1974) and are replotted here in Figure 11. Although Thomas' experiment was not specifically designed to assess the effects of increment size on PR performance, each rat was exposed to three different step-size conditions (following the development of stable responding in each step-size condition, multiple air-pressure assays were conducted -- see Pressure and/or Content of Air section, in the Introduction).

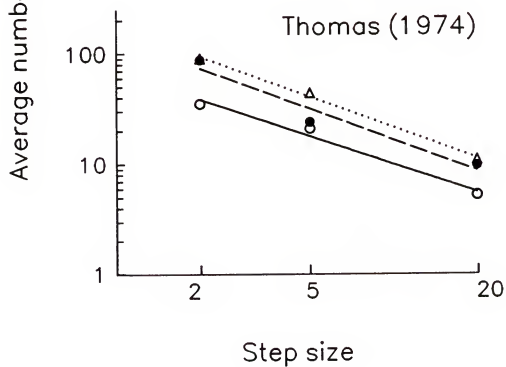
Figure 11 (top panel) shows data for two rats in Hodos and Kalman's (1963) experiment. The solid lines correspond with one subject and the dashed lines with the other; open symbols refer to data collected during conditions in which the rats' body weights were held at 80% of free-feeding weight, and closed symbols refer to data

Figure 11. Average number of completed ratios per session as a function of PR step size for subjects in Hodos and Kalman's (1963) and Thomas' (1974) experiments (data were estimated from each report's Figure 2). The straight lines show the best-fitting functions for each subject's data. In the upper panel, open symbols correspond with data collected during restricted-food-intake conditions, and filled symbols correspond with data collected during free-feeding conditions. Dashed lines show data from one subject and solid lines show data from the other subject. In the lower panel, individual-subject data are represented by the different symbols and line types. Note that both axes are scaled logarithmically in both panels.

Hodos and Kalman (1963)



Thomas (1974)



collected during conditions in which rats had free access to food in their home cages (the reinforcer in this study was sweetened condensed milk). The bottom panel shows data from three rats in Thomas' (1974) experiment. Summarizing across subjects in both studies, the average number of ratios completed declined across increasing step sizes. Although only a few step-size conditions were studied in either of these experiments, the general pattern of data points is consistent with that observed in the present study -- the declines in average number of completed ratios appear fairly linear in log-log coordinates. Power functions described these data well; the best-fitting functions produced R^2 values of .95 or above for every subject (Range: .95 to .99). Values of the parameter a for each subject in Thomas' (1974) experiment were similar to those observed in the present study, ranging from -.84 to -.93, but, as expected from the fact that average breaking point increased as step size increased, the values of a in Hodos and Kalman's (1963) study were significantly smaller (in absolute value) for both subjects in both conditions (during food deprivation, the values were -.60 and -.65, and in free-feeding conditions, the values were -.54 and -.71). The parameter b ranged from 68.92 to 178.62 in Thomas' (1974) study, and from 45.15 to 97.06 in Hodos and Kalman's (1963). All but one of these b values (not 45.15) fell within the range of those reported here.

In sum, power functions provided reasonable descriptions of the ratios-completed data reported by Hodos and Kalman (1963) and Thomas (1974). Values of both free parameters a and b generally approximated those calculated in the present experiment, except that the slopes of the functions from Hodos and Kalman's (1963) data were shallower than the rest. This general finding, that the functional relation between average number of completed ratios per session and step size generated in the present experiment can be identified in a retrospective analysis of previous reports, supports the notion that future research could replicate and extend upon the present

study. Moreover, Hodos and Kalman's (1963) data also provide a precedent in which this functional relation itself was shown to be sensitive to the application of an experimental treatment (i.e., the function served as a baseline). Figure 11 (top panel) shows that restricting subjects' food intake resulted in upward shifts of the function for each rat, relative to those observed during free-feeding conditions. The values of parameter b increased from 66.49 to 97.06 for one subject and from 45.15 to 77.03 for the other, reflecting this upward shift, whereas a values remained relatively stable (a increased for one subject and decreased for the other, but both changes were slight: from $-.54$ to $-.60$ in one and from $-.71$ to $-.65$ in the other). Hence, the speculations offered above, concerning the use of this inverse relation between the average number of ratios completed per session and step size as a baseline against which the effects of other variables (e.g., drug administration, lesions of the brain, etc.) might be assessed, cannot be considered too farfetched. Such a demonstration can be found in the existing literature. In addition, Hodos and Kalman's (1963) study showed that an experimental treatment can affect parameters a and b differently. Whether certain clusters of experimental treatments generally affect only one or the other of the two parameters remains a topic for future research.

Relations with Behavioral Economics

The present results could also be interpreted with respect to concepts and principles developed in the field of behavioral economics. More specifically, the relation between step size and the average number of ratios completed per session can be interpreted as a kind of "demand curve," which generally refers to the relation between the price and the consumption of a commodity (the present characterization of behavioral economics is based largely on that of Hursh, 1984). In conventional behavioral-economic procedures, price has been operationalized as the number of responses required for production of an item, and the average price is generally held

constant within an experimental session (i.e., an FR schedule often controls the relation between responding and production of the item of interest). A demand curve, showing the average number of completed ratios (or the total number of reinforcers earned) in a session as a function of FR value (i.e., price), can be generated by arranging different FR response requirements across conditions.

A PR schedule, on the other hand, arranges for the price of a commodity to increase within each experimental session. Because of this, a sort of demand curve can be generated in a single session; the dependent variable in this arrangement, however, differs from that generated by more typical procedures. In an FR-based procedure, the average number of completed ratios (calculated across sessions) can serve as the measure of consumption, whereas in a PR-based procedure, performance on each successive ratio would serve as the measure of consumption (i.e., consumption is quantal at each price -- either a ratio is completed or it is not). The two procedures might be considered indices of different aspects of consumption and demand: The FR-based method describes consumption in a situation in which prices are constant over extended temporal intervals, with demand curves emerging across conditions, whereas the PR-based method describes both consumption and demand in a more dynamic and temporally restricted circumstance.

Systematic alterations in the PR step size can also be interpreted with reference to the concepts of consumption, price, and demand. Different step sizes may be described as different patterns of increasing prices within experimental sessions. The price required for the production of a commodity increases more rapidly, in absolute terms, with larger step sizes (e.g., in a PR 5 schedule, absolute price increases by 5 responses each time a ratio is completed; in a PR 100 schedule, absolute price increases by 100 responses with each ratio completion). In proportional terms, however, increases in price are equivalent across different step sizes (this is true only for PR

schedules with arithmetically increasing response requirements). For example, in a PR 5 schedule, the proportional increase in response requirements from the first ratio to the second is 2.0 ($10/5 = 2.0$), from the second to the third is 1.50 ($15/10 = 1.50$), and from the third to the fourth is 1.33 ($20/15 = 1.33$). Similar proportional increases are arranged by a PR 100 (e.g., $200/100 = 2.0$, $300/200 = 1.50$, and $400/300 = 1.33$). It does not seem unreasonable to suggest that consumption of a commodity would be influenced by the pattern of increasing prices arranged by different PR step sizes. In fact, data from the present experiment show that pigeons' consumption of food (as indexed by the average number of ratios completed per session) decreased as a function of increasing step sizes. In other words, consumption of food was greater when absolute price increased relatively slowly; when absolute price increased rapidly, consumption declined. The function relating the average number of completed ratios per session with step size, then, could be translated into economic terminology as the following: "as the price of food increased more rapidly, consumption of food decreased in a proportional fashion."

If consumption of a commodity declines with increases in price, the corresponding demand curves can be described as "elastic" (Hursh, 1984). This is to be contrasted with an "inelastic" demand curve, which refers to a situation in which consumption of a commodity remains relatively constant despite increasing prices. Of course, these terms merely describe positions on a continuum, rather than absolute differences between commodities. The price for any commodity can be set at a value high enough to ensure that consumption will decrease, even for those commodities that are necessary for survival (e.g., food, water, oxygen, etc.). Hence, the terms "elastic" and "inelastic" are most appropriately used to describe patterns of consumption across a more limited price spectrum. The present results, it may be noted, indicated that the demand for food was elastic for pigeons, at least within the current procedural context.

A demand curve's relative elasticity may be influenced by a number of methodological factors. For instance, the degree of elasticity might be altered by the relative availability of the commodity in question outside of the experimental context. For instance, if a pigeon were given access to food outside of the experimental context, the relation between price and consumption might differ from conditions in which the pigeon's pecking during experimental sessions produced its entire daily rations. The former circumstance has been described as an "open economy," and the latter has been termed a "closed economy" (Hursh, 1984). The present experiment employed an open economy, since daily supplemental feedings were provided in the subject's home cage when they were necessary to maintain a pigeon's body weight at 80% of the free-feeding value. The degree to which the present findings are limited to an open-economy context is unknown. An empirical exploration of this question might be a fruitful course for future research to follow.

A final relation between the present results and economic terminology to be explored here concerns the concept of "unit price" (Bickel, DeGrandpre, Higgins, & Hughes, 1990). Unit price was developed primarily in the field of drug-self-administration, in which it has been defined as the ratio of responses per dose of drug delivered (but the concept has been extended to non-drug reinforcers, e.g., Hursh et al., 1988). For example, if 100 responses were required for a 20 mg infusion of a drug, the unit price would be 5.0 responses/mg. Several reports (e.g., Bickel et al., 1990; Bickel, DeGrandpre, Hughes, & Higgins, 1991; Bickel, Hughes, DeGrandpre, Higgins, & Rizzuto, 1992; DeGrandpre, Bickel, Hughes, & Higgins, 1992; English, Rowlett, & Woolverton, 1995) have demonstrated that consumption of different drugs is an orderly function of unit price. In general, as unit price increases, consumption decreases, and the declines have appeared fairly linear in log-log coordinates over a

broad range of unit prices (but, in several cases, consumption at the largest unit prices deviates from its linear decline, e.g., English et al., 1995).

Hursh, Raslear, Shurtleff, Bauman, and Simmons (1988) proposed an equation to describe this pattern of consumption:

$$\ln(Q) = \ln(L) + b[\ln(P)] - a(P),$$

where Q refers to the predicted consumption of the reinforcer, P refers to unit price, L corresponds with consumption at the lowest unit price measured, b refers to the slope of the curve at the lowest unit price measured, and a is the acceleration in slope observed across increasing unit prices. If the latter parameter is set to zero, this equation is indistinguishable from a logarithmically transformed power function (i.e., a power function of the form $y = b * x^a$ transforms into $\ln(y) = \ln(b) + a[\ln(x)]$, in which "x" refers to step size). In other words, the relation identified between the average number of completed ratios per session and step size in the present experiment may be considered a special case of the above equation (in the present experiment, unit price could be expressed as number of responses/1-s access to grain). It is not clear why a slope-adjusting factor was not required to provide a reasonable description of the present data. Regardless, spelling out the relations between unit-price analyses and mathematical descriptions of performance on PR schedules of food delivery might serve as an empirical and conceptual bridge between basic behavioral analysis and behavioral-economic analyses of drug self-administration or other kinds of consumption.

A Short List of Potential Research Questions

As noted above, the predictable relation observed in the current study between average number of completed ratios per session and step size could function as a baseline condition for virtually every research program summarized in the Introduction. For example, a broad audience of investigators might be interested in whether the

present results could be replicated using PR schedules with geometrically increasing response requirements. The only previous report concerned with this topic (Uzono, 1979) generated contradictory data across conditions (i.e., in one condition, breaking points increased with larger step sizes, and in another, step sizes had no effect on breaking point). A thoroughly parametric analysis of the effects of step size on PR performance in geometric progressions could provide data necessary to specify the generality of the present results. Since most investigators using PR schedules to study self-administration of drugs employ geometric progressions, such an analysis might begin to help determine the manner in which procedural differences across laboratories influence performance on PR schedules of drug delivery.

For that matter, the present procedures could be replicated more directly by those studying drug self-administration. Virtually no research in this area has been conducted using PRs with arithmetically increasing response requirements, and it might be interesting to characterize the similarities and/or differences between performances maintained by geometric and arithmetic PRs. For simplicity's sake, one might hope that assessments of a drug's relative reinforcing efficacy would not depend greatly upon such a subtle feature of the assessment procedure. It would not be too surprising, however, to find that relatively minor differences in the schedule of drug delivery can exert considerable control over the stable patterns of behavior observed. Schedules of reinforcement are notorious modulators of the effects of other independent variables on a given behavioral baseline (e.g., Kelleher & Morse, 1968; Sidman, 1961; Zeiler, 1984).

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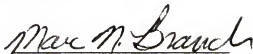
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BIOGRAPHICAL SKETCH

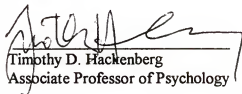
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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.



Marc N. Branch, Chairperson
Professor of Psychology

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.



Timothy D. Hackenberg
Associate Professor of Psychology

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.



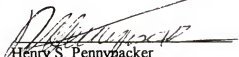
Brian A. Iwata
Professor of Psychology

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.



Mark H. Lewis
Professor of Psychiatry

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.



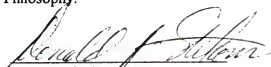
Henry S. Pennybacker
Professor of Psychology

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.



Alan Spector
Associate Professor of Psychology

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.



Donald J. Stehouwer
Associate Professor of Psychology

This dissertation was submitted to the Graduate Faculty of the Department of Psychology in the College of Liberal Arts and Sciences and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

May, 1996

Dean, Graduate School